AVATARS OF A MATTER–ANTIMATTER UNIVERSE[a]

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An elegantly symmetric Universe, consisting of large islands of matter and antimatter, is by no means obviously out of the question. I review the observations that lead to the usual *prejudice* that the Universe contains only matter. I discuss recent work [1] inferring that this prejudice can be converted into an inescapable conclusion. I argue that our theoretical conviction should not discourage direct searches [2] for antimatter in cosmic rays.

1 Evidence against cosmic antimatter

The Universe contains lots of light (some 400 microwave background photons per cc), a little matter (a few baryons and electrons for every billion photons) and practically no antimatter, at least in our neighbourhood. This is a surprisingly unbalanced recipe. I discuss how, on the basis of empirical observations and conventional physics, and on very general theoretical grounds, one can *prove* that our Universe contains no significant amounts of antimatter [1].

The possibility that there be matter and antimatter "islands" in the Universe has received occasional attention [3]. Early attempts to construct such a theory, notably by Omnès [4], were not successful. They faced the impossible and self-imposed task of separating the ingredients from their mixture. For domains of matter and antimatter to be present, baryogenesis and "antibaryogenesis" must have occurred in large separate domains.

In 1976 Steigman thoroughly reviewed the theory and observations of cosmic antimatter [5]. This work is still very much up to date, particularly in its recounting of observational constraints; much of the discussion in this section relies on it.

1.1 Antimatter about our planet

Various balloon- and satellite-borne detectors have observed cosmic-ray positrons and antiprotons. Their flux is compatible with the expectation for the secondary products of conventional (matter) cosmic rays impinging on interstellar matter (gas and dust). The $\bar{p}/p$ ratio is expected to diminish precipitously below a kinetic energy of a few GeV: at the high energy required to produce these secondaries, the production of a slow $\bar{p}$ is unlikely. The 1981 observation [6] of a large $\bar{p}$ excess at $E_{\mathrm{KIN}} \sim 0.1$ GeV created a stir: it could be fashionably interpreted as the result of galactic-halo dark-matter neutralino–neutralino annihilation. Subsequent observations [7,8] brought the $\bar{p}$ flux back to the standard expectations. There is also a hint –in no way significant– of a low-energy positron excess [9,8].

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[a]Based on a talk at the January 1998 Moriond Meeting at Les Arcs, France.

The cosmic-ray flux of many different nuclei is well measured in a domain of kinetic energy (per nucleon) extending from a few MeV to circa 1 TeV. But for a small fraction of anti-deuterons, one does not expect an observable flux of antinuclei, for the energy required to make these fragile objects in matter–matter collisions is far in excess of their binding energy. No convincing observation of $Z > 2$ antinuclei has been reported. It is often emphasized that the observation of a single antinucleus would be decisive evidence for an antimatter component of the Universe: it is likely that $\overline{\text{He}}$ would be the result of primordial antinucleosynthesis; $\overline{\text{C}}$ would presumably originate in an antistar.

1.2 Antimatter in our galaxy

The picture of Armstrong's footprint on the lunar surface is the most convincing evidence that the astronaut and the Moon were made of the same stuff. The planets, asteroids and comets of the solar system are also of uniform composition. The solar wind (mainly protons) would otherwise shine in observable gamma rays as it impinges on their surfaces or atmospheres.

Observations of the 0.511 MeV e^+e^- annihilation line in the direction of the galactic center, particularly by the OSSE instrument on board of the Compton GRO satellite [10], show an interesting distribution of annihilating positrons. Their origin can be quite unsurprising: β^+ decay products of elements synthesized in supernovae, novae, and Wolf-Rayet stars [11].

Of the various constraints on a possible contamination of antibaryons in our galaxy, the most stringent pertains to observations of hydrogen in "clouds". Gamma rays from their directions are observed; they are compatible with π^0 decay, the pions being secondary products of collisions of ordinary cosmic rays with the hydrogen in the clouds. The non-observation of a γ excess implies that the antibaryon contamination in these media cannot exceed one part in 10^{15}, an astonishingly stringent result.

Galaxies are supposed to have undergone a phase of recollapse onto themselves, after they lagged behind the general Hubble expansion to become objects of fixed size, at a redshift of a few. This recollapse is reckoned to mix and virialize the galactic material, and to re-ionize its ordinary matter. If this process could occur in a galaxy containing matter and antimatter (a possibility to be doubted anon) it would annihilate the minority ingredient, or blow the galaxy apart. Nonetheless, the search for ordinary or neutron antistars is of interest, for they may not "belong" to our galaxy, but be intruders from afar. These objects would accrete interstellar gas and shine γ rays. At the time of Steigman's review, the point-like and diffuse limits were: no single antistar in our 30 parsec neighbourhood, no more than one antistar for every 10^4 ordinary ones. I do not know whether these limits have been subsequently updated.

1.3 Antimatter beyond our galaxy

The "photonic" astronomer cannot determine whether or not another galaxy is made of matter or of antimatter. But galaxies in collision are often observed: the Antennae pair NGC4038(9) is a gorgeous example. An encounter involving a galaxy and an antigalaxy would be spectacular. No such event has been reported.

The largest objects on whose "purity" we have information are clusters of galaxies. Some of them are sufficiently dense and active to sustain an intergalactic hot plasma in their central parts, at a temperature of order 10 keV. The failure to observe a γ-ray excess atop the thermal spectral tail implies a purity at a level of a few parts per million. Clusters of galaxies (of a
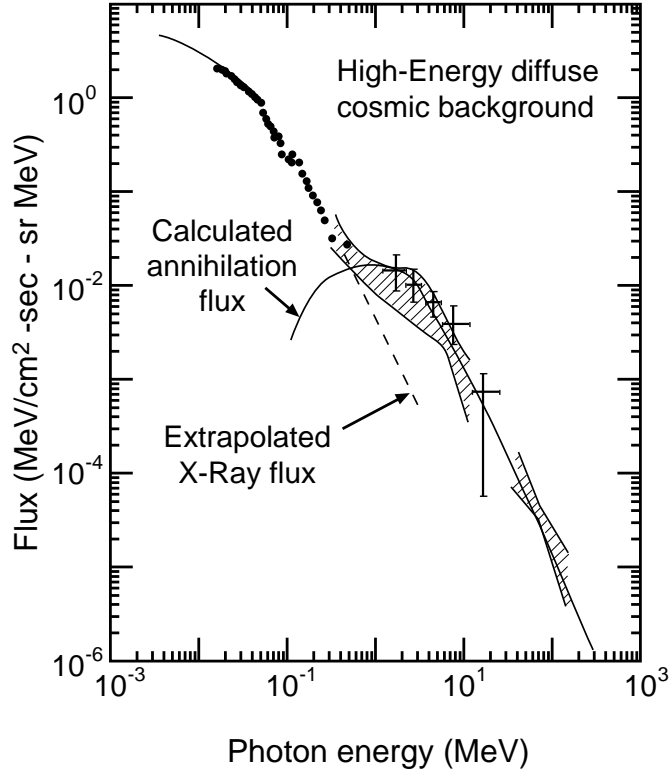
Figure 1: Energy flux of the diffuse γ-ray spectrum.

typical size O(20) Mpc, or 6×10^7 light years) are the largest objects empirically known to have a uniform composition.

In 1971 Stecker *et al.* [12] studied a matter–antimatter Universe in which, somehow, a *fixed* (time-independent) fraction of the average baryon (or antibaryon) density is continuously annihilating. They could choose that fraction so that the (redshifted) photons from $\bar{p}p$ annihilation would reproduce the (then) observed shoulder or hump at ~ 2 MeV in the cosmic diffuse γ-ray spectrum (CDG), see Fig. 1. The ingredients of their cosmology are by now outdated, and the presence of the hump, as we shall see, is debated [13].

2 Conclusions at this early stage

Define a *domain* to be a region of the Universe whose typical dimension today is d_0, with $d_0 \geq 20$ Mpc. The radial extension of the visible Universe is a few thousand Mpc; it contains as many as 30 million domains. Given the observed abundance of galaxies, each domain would in turn contain, on average, at least a few thousand galaxies or antigalaxies.

We have seen that there are also empirical arguments whereby clusters of galaxies (regions similar to or smaller than the domains we have defined) ought to be made of either matter or antimatter. Our own domain, by definition, is made of matter. It is a common but considerable extrapolation to conclude from this single example that the rest of the tens of millions of visible domains are also made of *matter*.

Imagine a patchwork Universe made of regions of matter and antimatter. Suppose that each region is currently larger than 20 Mpc and contains either galaxies or antigalaxies. At this point of my talk, it is **NOT** observationally excluded that some domains in the Universe (say half of

them) be made of antimatter. Thus, it behooves one:

- to try and improve the 20 Mpc limit on the domain size d_0, by reexamining the constraints imposed by current observations[1];

- to try and improve the $d_0 > 20$ Mpc limit by undertaking novel observations[2].

3   Extant views on cosmo- and baryogenesis

At a very early age, it is argued, the Universe "inflated" superluminally, with a scale factor $R(t) \propto t^n$, $n > 1$; or $R(t) \propto \exp[H\,t]$. Inflation can tell why the cosmic background radiation (CBR) is so uniform, how the cosmic structures may have evolved from inevitable quantum fluctuations, why the density of the Universe at its ripe old age (in the natural Plank-time units) is so close to critical, how its enormous entropy could have evolved from a primeval state of extreme simplicity ... No alternative scheme competes with inflation in its explanatory power.

In the conventional picture, baryon–number–violating interactions are prevalent in the very early Universe, so that the concept of an initial baryon number in not meaningful. As Sakharov prophesied, the interplay of CP- and baryon-number-violating interactions, in a period far from thermal equilibrium, could have led to a universal baryon asymmetry; that is, to baryon and antibaryon densities satisfying $n_B - n_{\bar{B}} > 0$ *everywhere.* In this scenario, there would be today no cosmologically significant amounts of antimatter in the visible Universe.

It goes without saying that in order to imagine an unconventional Universe consisting of matter and antimatter domains, several observational and theoretical constraints must be satisfied: sufficient inflation must have taken place to reproduce the successes of standard inflationary scenarios; the standard picture of primordial nucleosynthesis must survive unscathed; a mechanism must be present to generate the inhomogeneities seen in the CBR and those argued to be the seeds of subsequent structure formation; the CBR must be close enough to thermal and uniform to conform to observations; the surviving flux of γ-rays from matter–antimatter annihilations at domain boundaries must not exceed the diffuse γ background.

4   A symmetric Universe

4.1   Sketch

My colleagues Belén Gavela and Andy Cohen (and I)[14] have studied a variety of theoretical scenarios for a symmetric cosmology. Tenable alternatives share many features. In particular, by the time of nucleosynthesis, the Universe must consist of large matter or antimatter regions of uniform density, separated by narrow interstices that are not (or no longer are) domain walls. The subsequent evolution of this early state and its confrontation with the observed Universe are independent from its origin, and may be studied separately[1].

Our models of the generation of separate domains of matter and antimatter (DMAs) are based on a Zen maxim: *If you find a fork on the road... take it!* Thus may domains of cluster size or bigger, as they depart from the horizon during inflation, take "roads" leading to the two possible signs of the baryon-number excess.

Our DMA Universe is not unlike a magnetic material cooled below its Curie point. Even a flawless material, if large enough and cooled rapidly, would not become a domain with a single magnetic direction, for the speed at which the information travels (the spin-wave velocity) is

finite. Our analogue of magnetization is the field the sign of whose phase determines the baryon or antibaryon excess. Let $\Delta \equiv n_B - n_{\bar{B}}$. The difficulty for us is to end up with domains of a very well defined $\Delta \simeq \pm|\Delta_0|$ (only "up" or "down" magnetization, but very little in between). We must accomplish this, because if there were domains with different baryon (or antibaryon) densities –and thus different mass densities– the abundances of primordial elements and the CBR's temperature would show unacceptable inhomogeneities. As it turns out, this constraint is not unduly difficult to satisfy.

Ours is an inflationary scenario and it shares with others the necessity to choose an arbitrary set of parameters (there being no theory of everything, in spite of millenarian claims to the contrary). To the conventional lore we must add one arbitrary parameter that determines the average size d_0 of the DMAs. It turns out not to be difficult to construct a theory for which the distribution of DMA sizes is very sharply cutoff for sizes smaller than a given d_0. This is good, for the occasional small antimatter domain in a larger matter region would represent a serious observational problem.

As baryogenesis (and anti-baryogenesis) proceed as in conventional scenarios, we are left with a patchwork Universe of regions of (current) correlation-size d_0 randomly containing only matter or only antimatter, separated by contact zones of negligible width, relative to d_0. To figure out the fate of these frontiers –as the Universe evolves from a dense plasma of many species of particles to its present status– is a lengthy but edifying exercise in conventional physics.

One good reason not to indulge in a more detailed description of our models is that they belong to the very general class that we shall now proceed to infirm.

4.2 Annihilation is inevitable

From afar, the only way to tell about the presence of both matter and antimatter is to observe the direct or indirect effects of annihilation. Imagine a scenario in which matter and antimatter are separated by voids. How could it possibly be refuted? As it turns out, the observed uniformity of the CBR excludes the putative voids, independently of whether they separate matter from matter or matter from antimatter (topological walls could also do the job, but their parameters would have to be very arbitrarily concocted if they are to act as matter–antimatter buffers and yet not contribute in excess to the universal energy density).

At a temperature ~ 0.25 eV, corresponding to a redshift $z_R \sim 1100$ the primordial plasma turned to neutral atoms (recombination) and the radiation decoupled from ordinary matter (last scattering). The transition to transparency occurred during an interval $z_R \pm 100$, endowing the last scattering "surface" with a current (expanded) width of ~ 15 Mpc (an angular bracket $\Theta_{LS} \sim 8'$ in the transverse direction). This angle is the resolution of the "picture" of the CBR: smaller features at recombination cannot be discerned. (Some of the precise numbers I quote are specific to a ten–billion–year–old, critical, dark–matter–dominated Universe, but the conclusions do not depend on this particular choice).

Voids would be non-homogeneities in the baryon density. Such fluctuations are damped, at $z < z_R$, by photons diffusing out of the over-dense regions and dragging matter along with them. By recombination, inhomogeneities with current sizes < 16 Mpc would be destroyed by this mechanism [15]. This bound fortuitously coincides with Θ_{LS}: voids large enough to survive until recombination would have been seen in the CBR. Since they are not, we conclude that matter and antimatter regions must be in contact after recombination. The *minimal* signatures of a baryon symmetric Universe result from annihilations taking place at $z < z_R$.

The evolution of a nearly uniform primordial Universe into today's splotchy structure is not understood well enough to state its effect on matter–antimatter annihilation. To avoid immediate trouble, it must be unlikely for a galaxy or a cluster to contain comparable amounts of matter and antimatter. For such structures to grow (rather than "to ring") from the gravitational evolution of a mass overdensity, a "Jeans condition" must be satisfied, the sound travel time across the inhomogeneity l/v_s must be longer than the gravitational collapse or free fall time $1/\sqrt{G\,\rho}$. That is, $G\,l^2\,\rho \geq v_s^2$. If equality were approached for a region containing both matter and antimatter, annihilation would reduce ρ, driving the system away from collapse. Thus, one does not expect a matter–antimatter domain boundary to cut through a galaxy or cluster of galaxies. Grown-up density inhomogeneities should be of uniform composition. To be conservative in assessing annihilation signatures we must "turn them off" as soon as structure formation becomes non-linear at some scale. For the corresponding redshift we follow Peebles [16] in adopting the value $z_S \simeq 20$. A 50% up or down modification of this choice does not affect our conclusions.

Annihilation is inevitable in the interval $z_R > z > z_S$.

4.3 Explosive dynamics

Imagine placing two semi–infinite gaseous regions, one containing hydrogen, the other anti-hydrogen, in contact along a plane. One's first impression is that the result would be a fairly violent run-away process, the dream of the combustion engineer: the gases would move towards a zone of overlap and annihilation, the annihilation products would heat the gases, which would move faster towards annihilation, producing more heat...

For the matter densities characteristic of the early Universe, one's first impressions are not always right. For one thing, at redshifts $z < z_R$, the Universe is quite transparent to the photons resulting from $p\bar{p}$ or e^+e^- annihilations. A small fraction of these photons interacts, but they deposit their (redshifted) energy far away from an annihilation region: they do not trigger an explosive reaction. Apart from irrelevant neutrinos, the only other stable ashes of H–$\overline{\text{H}}$ annihilations are electrons and positrons of tens of MeV energies, made in $\pi \to \mu \to e$ decays. Their behaviour in the early Universe is peculiarly complicated, and their role is crucial. In practice, the difference between what electrons and positrons "do" is irrelevant, and I shall refer to both species simply as electrons.

The electromagnetic shower made by the electrons is unlike anything you have seen in the laboratory. The electron energy loss along its trajectory, dE/dx, is dominated by scattering, not on the ambient matter, but on the ambient light: the CBR. The CBR photons are Compton scattered by the relativistic electrons from their thermal energy to energies $\sim (E_e/m_e)^2$ times larger. The up-scattered photons have enormous ionizing cross sections on hydrogen. As a result, at distances within the electron range from a layer of matter–antimatter contact, and for the reckoned annihilation rate, the plasma stays fully ionized after recombination, during all the epoch $z_R > z > z_S$ of interest to us.

In the medium they keep ionized, less than 1% of the energy of the annihilation electrons is lost in collisions with ambient electrons or nuclei. But this small fraction is sufficient to produce, in the vicinity of a region where annihilations are taking place, a significant heating of the ambient matter, whose thermal history thus departs from the standard evolution.

The thermalized energy deposited by electrons increases the rate at which the matter and antimatter fluids converge towards their annihilation, accelerating this process and the subsequent local heating. While in the absence of this reheating it is possible to give analytical
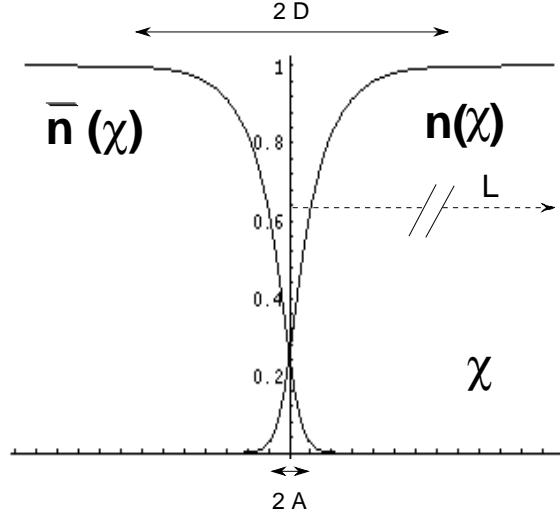
Figure 2: An artist's impression (not to scale) of the density profile of matter and antimatter at a domain boundary.

approximations to the quantity of interest (the annihilation rate as a function of time), the real problem requires a numerical solution to the equations for the fluids' motion.

4.4 Just a few equations

Various approximations are adequate to our analysis, at least in the interval $z_R > z > z_S$. All matter particles maintain a common local temperature, not necessarily coinciding with the CBR temperature, which follows its conventional redshift dependence $T_\gamma = T_0 (1 + z)$, $T_0 \sim 2.7$ K. Elements heavier than hydrogen can be neglected. The decay products of $e^+ e^-$ annihilation play an insignificant role, the process can be ignored. Let $A(z)$ be the length scale over which matter and antimatter fluids overlap and annihilate, let $D(z)$ be the size of the domain depleted by motion towards the annihilation region, and let $L(z)$ be the width of the region heated by the products of annihilation, all as in Fig. 2. At all times $L > D > A$ by one or two orders of magnitude. The minimum size of a matter or antimatter domain evolves as $d = d_0/(1 + z)$ and turns out to be larger than the other relevant scales. Thus the curvature of the boundary surfaces between domains can be neglected: the fluid motion and annihilation problem is one-dimensional, with mirror symmetry between matter and antimatter.

Let R be the universal scale factor, and χ a comoving variable, with $\chi = 0$ at the symmetry plane. Let n, v, T and P be the proton (or electron) number density, velocity, temperature and partial pressure. The antimatter quantities are $\bar{n}(\chi) = n(-\chi)$, $\bar{v}(\chi) = -v(-\chi)$, etc. Baryon-number conservation dictates:

$$\frac{\partial n}{\partial t} + 3 \frac{\dot{R}}{R} n + \frac{1}{R} \frac{\partial (n v)}{\partial \chi} = - \langle \sigma_{\mathrm{Ann}}(p\bar{p}) \, v(p\bar{p}) \rangle \, n \, \bar{n} \, . \tag{1}$$

Energy conservation can be expressed as:

$$\frac{\partial P}{\partial t} + 5 \frac{\dot{R}}{R} P + \frac{1}{R} v \frac{\partial P}{\partial \chi} + \frac{5}{3} \frac{1}{R} P \frac{\partial v}{\partial \chi} = \frac{1}{2} n_\gamma \, \Gamma_{e\gamma} \, n \, (T_\gamma - T) + \frac{H}{3} \, . \tag{2}$$

The conventional first term on the r.h.s. describes the heat-bath effect of the CBR, with $\Gamma_{e\gamma}$

the rate of plasma–photon energy transfer:

$$\Gamma_{e\gamma} = \frac{4\pi^2}{45}\, c\, \sigma_t\, \frac{\pi^2}{\zeta(3)}\, \frac{T_\gamma}{m_e} \tag{3}$$

and σ_t the Thompson cross section. In the second term on the r.h.s. of Eq. (2), H is the "heat function": the energy deposited per unit volume and time by the annihilation debris in the ionized plasma. Let $dl = R\, d\chi$ and let $\langle dE/dl \rangle$ be the decremental energy loss to the plasma by a single electron, in the direction $\vec{l}$ orthogonal to the symmetry plane, averaged over the electron emission angles relative to $\vec{l}$. The heat function is simply $H = J_e\, \langle dE/dl \rangle$, with J_e the current of annihilation electrons. The electron current (into one side of the annihilation zone) is half of the $p\bar{p}$ annihilation current, J_p, times the electron multiplicity (roughly 3.8). Finally, J_p is the total annihilation rate per unit surface orthogonal to $\vec{l}$:

$$J_p = \int \langle \sigma_{\mathrm{Ann}}(p\bar{p})\, v(p\bar{p}) \rangle\, n\, \bar{n}\, dl \;. \tag{4}$$

Momentum conservation results in the third and last of the fluid motion equations:

$$\frac{\partial v}{\partial t} + \frac{\dot{R}}{R}\, v + \frac{1}{R}\, v\, \frac{\partial v}{\partial \chi} + \frac{1}{R}\, \frac{1}{n}\, \frac{1}{m_p}\, \frac{\partial P}{\partial \chi} = \frac{1}{2}\, \frac{m_e}{m_p}\, n_\gamma\, \Gamma_{e\gamma}\, v + \frac{H}{2n\, m_p\, c}\;. \tag{5}$$

The first term on the r.h.s. describes how the proper motion of the fluid is damped by friction of its electrons against the CBR. The last term is the momentum deposited in the reheating zone by $e^\pm$ from $\bar{p}p$ annihilation.

The solutions to Eqs. (1)–(5) depend on various cosmological parameters, notably the baryon to photon ratio $\eta \equiv n_B/n_\gamma \simeq n/n_\gamma$. We choose a value at the lower end of the observationally allowed domain ($\eta = 2 \times 10^{-10}$) since we are interested in the minimal annihilation signals. Their dependence on the rest of the parameters (Hubble and cosmological constants, departure from closure) within their empirically allowed range does not amount to more than a factor ~ 3 and does not affect the conclusions. I shall give results for $H_0 = 75$ km/s/Mpc, $\Lambda = 0$, $\Omega = 1$, implying $R \propto t^{2/3}$ in the redshift interval of interest.

The solutions to Eqs. (1)–(5) are qualitatively different at large and small redshifts. For $z > 400$ the CBR drag force dominates so that the motion is diffusive. In these early times the CBR is also an effective heat bath that keeps matter in thermal equilibrium with radiation everywhere, even in regions reheated by annihilation. This early diffusive period has a welcome consequence: all memory of the initial conditions is lost as the fluid evolves. The post-recombination annihilation signal does not depend on the (pre-recombination) time at which matter and antimatter domains first come into contact. For $z < 400$ the pressure-gradient dominates the CBR-drag so that the fluid motion is "hydrodynamic". Moreover, heating due to the annihilation electrons plays an important role. Positive feedback sets in to increase the annihilation current. This potentially runaway process is eventually quenched by rarefaction. For $z < 30$, the Universe is so sparsely populated that cooling by expansion dominates the evolution of the matter temperature.

The terms representing CBR drag and annihilative heating ensure that the matter temperature in the moving fluids is spatially constant. The computed value of this temperature is shown as a function of $y = 1 + z$ in Fig. 3, where it is compared with the temperature beyond the reheating zone (as it would be in an all-matter Universe).
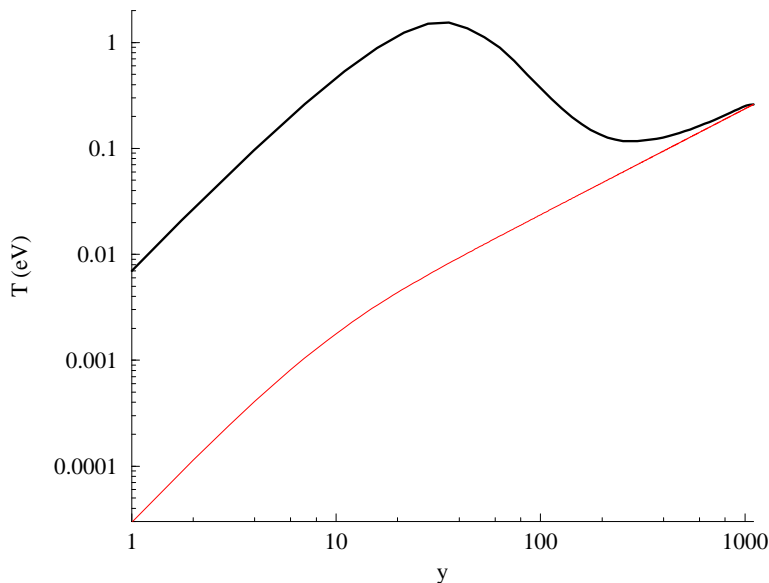
Figure 3: Temperature (in eV) as a function of redshift $y = 1 + z$. The upper curve is our numerical solution. In the lower (conventional) curve, reheating is ignored[1].

5   Annihilation signatures

The solution of the fluid annihilation equations provides the annihilation current J_p of Eq. (4) as a function of redshift. We do not live close to an annihilation zone, and we are mainly interested in the non-local, or "diffuse" collective effects of annihilation throughout the Universe. These depend on the rate of annihilation per unit *volume* and time (averaged over a region large enough to encompass various matter and antimatter domains) which is J_p/d, with $1/d$ their average surface-to-volume ratio (d expands as $d = d_0/y$).

5.1   The cosmic diffuse gamma-ray background (or CDG)

Let $\Phi(E)$ denote the (lab) inclusive photon spectrum per $p\bar{p}$ annihilation. The average number of photons made per unit volume, time and energy is $\Phi(E) J_p/d$. Let $N(E, y)$ be the flux of annihilation photons (per unit time, area and solid angle) reaching a point with redshift parameter $y = 1 + z$. This flux evolves according to a "renormalization group" equation:

$$\left(y\frac{\partial}{\partial y} + E\frac{\partial}{\partial E} - 2\right) N(E, y) = \int g(E, E', y) N(E', y) dE' - \frac{c\,\Phi(E)}{H_0\, y^{3/2}} \frac{J_p(y)}{4\,\pi\, d(y)} \qquad (6)$$

where the first term on the r.h.s. is a correction for photon rescattering and the second is the annihilation source. The current flux is $N(E, 1)$. In solving this equation, we "switch on" the source only in the redshift interval $z_R > z > z_S$.

The observed CDG flux is compared to our (conservative lower limit) flux $N(E, 1)$ in Fig. 4. In the 2–10 MeV energy range, recent preliminary COMPTEL satellite measurements [17] lie roughly an order of magnitude below the earlier balloon data [18-23]. Two theoretical results are shown: the upper curve is for $d_0 = 20$ Mpc, the lower one for $d_0 = 1000$ Mpc. The $N(E, 1)$ spectrum is redshifted from the spectrum at production (which peaks at $E \sim 70$ MeV), and
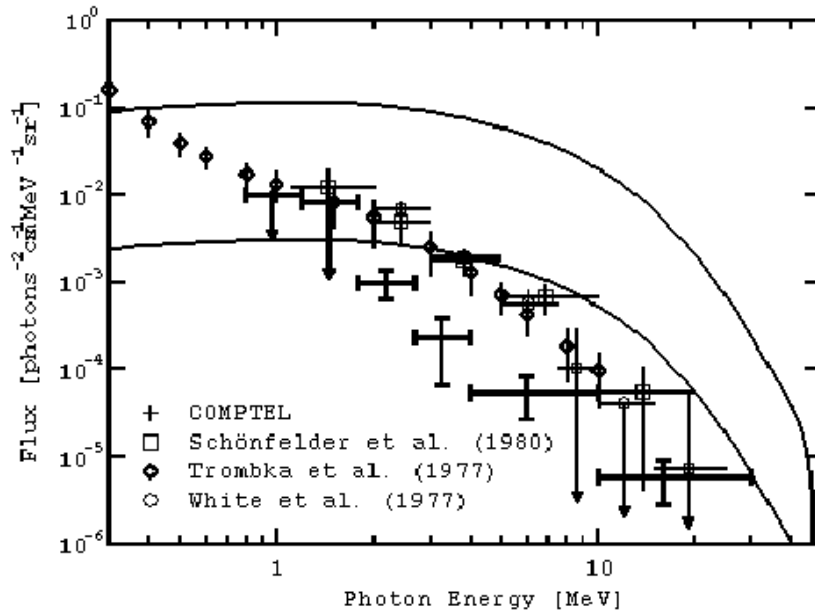
Figure 4: Data and expectations for the number-flux diffuse γ-ray spectrum[1].

is slightly depleted at the lowest energies by attenuation. The $d_0 = 10^3$ Mpc result is barely compatible with the balloon data, and an order of magnitude above the satellite data. To reach agreement, d_0 must be comparable to or larger than the current horizon.

The conclusion is clear: the diffuse gamma-ray observations completely exclude a Universe containing significant amounts of antimatter. Are the constraints from the much-better measured CBR comparably stringent?

5.2 Distortion of the CBR

Matter–antimatter annihilation would make the CBR spectrum deviate from its thermal distribution. A flux of "Comptonized" photons is produced as the annihilation electrons scatter on the CBR. These populate a UV region of energies wherein the hydrogen photoionization cross section is extremely large. The UV photons reaching the border of the ionized domain deposit their energy in photoionization reactions. Through these secondary interactions, a fraction $f(y)$ of the energy of the original annihilation-product electron ends up as heat. (The fraction $f(y)$ is very weakly dependent on the initial electron energy, and is always close to unity; a lengthy exercise demostrates that $f(y)$ rises from $\sim 1/2$ at $y = 10$ to saturate close to 100% above $y = 300$.) The heated ambient electrons, in a third step, distort the CBR.

The Sunyaev–Zel'dovitch parameter Y characterizes the thermal distorsion as a frequency-dependent "temperature", a function of $x = \nu/T_0$:

$$T(x) \sim T_0 \left[1 + Y \left(\frac{x \, (e^x + 1)}{e^x - 1} - 4 \right) \right] \; . \tag{7}$$

The COBE results translate into $|Y| < 1.5 \times 10^{-5}$.

On average, and per $p\bar{p}$ annihilation, some $\Delta E \sim 320$ MeV of energy are carried away by electrons. The universally averaged energy per unit volume and redshift interval deposited by

the photoionizing interactions is:

$$\left|\frac{d\epsilon}{dy}\right| = \frac{1}{H_0\,y^{5/2}}\,\frac{J_p(y)\,\Delta E}{d(y)}\,f(y)\;.\tag{8}$$

Subject to this heat, the ambient electrons interact with the CBR, resulting in a predicted:

$$Y \simeq \frac{15}{4\,\pi^2}\int_{y_S}^{y_R}dy\,\frac{1}{T_\gamma^4(y)}\,\frac{d\epsilon}{dy}\tag{9}$$

where y_S and y_R are our consuetudinary redshift cut-offs.

To compute the value of Y in Eq. (9) one has to use the current J_p from the solution to our fluid equations. For $d_0 = d_{\min} = 20$ Mpc the result is $Y = 4.6 \times 10^{-4}$, exceeding by over one order of magnitude the COBE limit. To have theory comply with this observational stricture we must have $d_0 > 700$ Mpc. This limit is stronger than the one stemming from X-ray emitting clusters, but it is not as strong as the one we obtained from the diffuse γ-ray background.

6 Caveats?

We have tried to find a weakness in our *no-go theorem* stating that the Universe is indeed asymmetric in its matter/antimatter constituency. "Isocurvature voids" and primordial magnetic fields of a very specific nature are the only caveats we have found that we cannot exclude on the basis of observations and well established physics.

By isocurvature voids, I mean a scenario in which matter and antimatter islands would be separated by interstices with vanishing baryon density, but the photon distribution would be uniform. In models with isocurvature fluctuations, disfavored by observations of the CMB and of galaxy clustering[25], our arguments about matter and antimatter necessarily touching at recombination would not apply. We have not pursued this line of thought any further.

The effect of magnetic fields that are sufficiently strong and disordered (small correlation length) would be to shorten significantly the distance over which annihilation electrons deposit their energy. The reheating due to these electrons becomes more efficient, the effect goes in the direction of increasing the annihilation rate and improving our bounds. This is unless the electron reach becomes so short that the nature of the solution to our fluid motion equations changes drastically.

There is no known way to generate magnetic fields in the pre-recombination plasma by conventional dynamo effects; their production from the latent heat of some first-order phase transition is the most often invoked hypothesis[26]. If the primordial Universe was ever at a temperature exceeding the mass of the weak vector bosons ($T > T_W \sim 100$ GeV) it is natural to assert that electromagnetism was "born" in the phase transition that possibly occurred as the electroweak symmetry "broke". The question of whether such a transition could generate magnetic fields is debated, the details of the resulting field strength and structure are a matter of guesswork. Typical assumptions are a field energy density comparable to that of the other ~ 100 degrees of freedom acting at that time (or $B \sim 10^{24}$ gauss) and a correlation length one to three orders of magnitude smaller than the horizon (a mere 1.4 cm by then).

We have studied the evolution of primordial fields originating in an electroweak or QCD transition and we find that their effect is to increase the annihilation rate and strengthen our conclusions. But we cannot entirely exclude the existence of an *ad hoc* magnetic field structure with a correlation length much shorter than the ones we have studied, nor the possibility that the current understanding of magneto-hydrodynamics be insufficient to reach a definite conclusion.

7   Conclusions at 3/4 of the way

By the summer of 1974, a group at Brookhaven had detected, in the debris of hadronic collisions, a narrow peak at 3.1 GeV in the invariant mass of e^+e^- pairs. Practically every theorist would (then) have said that one could prove on general grounds, and beyond the shadow of a doubt, that something made with a hadronic-sized cross section and weighing as much as 3.1 GeV, HAD to be very broad: the data HAD to be wrong. This is to say that (though the standard model has accustomed us otherwise) theorists are apt to miss a point, if the point is big enough.

Astrophysics is a subject wherein surprises also pullulate. Quasars, pulsars, invisible mass, gamma-ray bursts and high energy cosmic rays would have been difficult to guess.

Finally, nothing can compete with *direct* limits or observations, e.g. of antinuclei in the cosmic rays. The above are three reasons to look for these alien creatures. I proceed to discuss one of the efforts in this direction.

8   Extragalactic cosmic rays

To reach us, a cosmic ray from a more distant galaxy (or antigalaxy) must have been able to exit from it, to travel all the way here, and to penetrate the galactic disk. This is feasible, as I proceed to outline (for details and numerous references, see Ref. 24). Intergalactic travel is the least problem. From the time of galaxy formation, the density of intergalactic matter has been far too small to intercept travelling nuclei. There are no solid grounds to believe that intergalactic space is permeated by magnetic fields strong enough to encumber the straight voyage of an energetic charged particle. A relativistic particle could reach us from the confines of the visible Universe.

Our galaxy has a microgauss magnetic field of complex structure. The average (charged) cosmic ray meanders around the galaxy for a "confinement time" at least a thousand times longer than the few thousand years it would take it to cross the galactic disk forthright. Could cosmic rays never escape, as in "closed galaxy models"?

Our knowledge of the history of cosmic rays is based on the study of their chemical and isotopic composition. The relative abundance of the various elements at the location where the rays are accelerated is presumed to be akin to that of the solar system. The "arrival" abundances are indeed generally similar to the solar ones, with a pronounced odd–even Z-variation and a peak for Fe, as befits elements that have been made in stars (H and He are primordial, and underabundant in cosmic rays).

Certain overabundances of cosmic rays (Li, Be, B and Sc to Mn) are attributed to the fragmentation of larger primary nuclei. The "leaky box" model, wherein cosmic rays are magnetically confined but have a chance of escaping the galaxy, is the simplest one to fit these observations. The (excellent) fit results in a value for the mean traversed column density (roughly 10 g/cm^2, for a kinetic energy of 1 GeV per nucleon). The confinement time is more directly bracketed (to 25 ± 10 Myr) by the abundances of ^{10}Be, whose lifetime is 2.3 Myr, and ^{9}Be, which is stable. Closed models are definitely excluded [27] by their inability to explain the ^{3}He-to-^{4}He ratio.

Cosmic rays are obstructed not only by the Earth's magnetic field, but also by the outflowing solar wind. Similarly, the "galactic accessibility" –the probability that an alien ray penetrates our galaxy– is affected by magnetism and by the halo galactic wind, driven by supernova explosions. The estimate [28] is that, at a kinetic energy/nucleon of 1 GeV, the accessibility may be 10–50%.

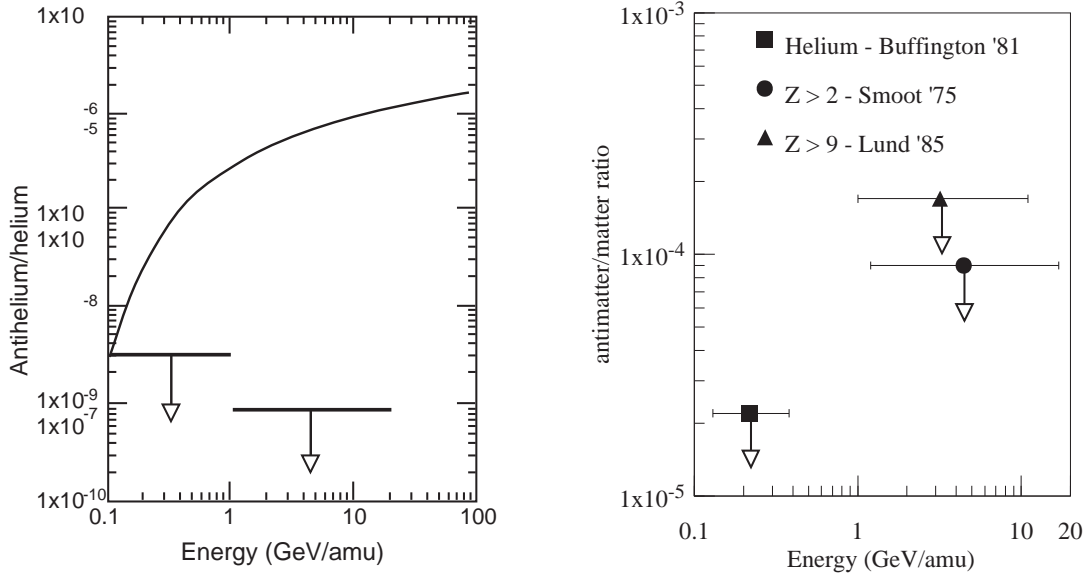Finally, one must estimate the fraction E/G of extragalactic to galactic rays. Meteorite

Figure 5: Left: $\overline{\mathrm{He}}$/He ratio, expectation in a symmetric Universe and reach of AMS (plateaus). Right: current limits on antinuclei in cosmic rays.

observations demonstrate that the cosmic-ray flux has been constant for at least 4 Gyr, consistent with an equilibrium between production and leakage. Assume the $t_{\mathrm{res}} \sim 25$ Myr cosmic-ray residence time in our galaxy to be typical. Galaxies have been around for some $t_{\mathrm{gal}} \sim 15$ Gyr. The volume fraction currently occupied by galaxies is f $\sim 10^{-7}$. Clearly, in a steady state of cosmic-ray production, moderate absorption, and subsequent leakage, $E/G \sim \mathrm{f}\, t_{\mathrm{gal}}/t_{\mathrm{res}} \sim 6 \times 10^{-5}$, to be further reduced by the accessibility factor.

All of the above considerations enter the calculation of the $\overline{\mathrm{He}}$/He fraction displayed in Fig. 5, for a hypothetical Universe made of equally many DMAs of size $d_0 = 20$ Mpc. The fraction is probably an underestimate; it assumes that cosmic rays diffuse in a maximally disordered magnetic field sustained by a hot intercluster plasma, once argued to be required to explain diffuse X-rays [29] and now excluded [30]. The difference between diffusive and straight travel reduces the effective reach of extragalactic cosmic rays from $l \sim 3000$ Mpc to $l \sim 150$ Mpc.

9   The Alpha Matter Spectrometer

Impervious to the relaxed progress of the theoretical work I have described, a team whose spokesperson is Sam Ting [2,24] has been busy designing and constructing the *Alpha Matter Spectrometer* (AMS), a device to be flown in Earth's orbit, meant to improve by many orders of magnitude our knowledge of cosmic rays.

The main detector of AMS is a small (~ 1 m^3) charged-particle spectrometer measuring charge (squared) from the energy deposition along a track, velocity with a time-of-flight device, and momentum (over charge) with a tracker surrounded by a magnet. The technological AMS break-through is in its magnet. Unlike that of previous projects [31], it is not a superconducting magnet necessitating liquid-He refrigeration, an added nuisance. It is a permanent magnet made of Nd–Fe–B crystals that can sustain an unprecedentedly strong magnetic field. Some of the current limits on cosmic–ray antinuclei, as well as the expected reach of AMS (a three to four orders of magnitude leap into unexplored land) are shown in Fig. 5.

The AMS proposal was approved by NASA and the DOE in 1995, and scheduled for a first test flight in the space shuttle, to be launched on the 2nd of April of 1998. The significance of this date should be clear: it is the anniversary of Hans Christian Andersen, the master of fairy tales. This maiden flight should last two weeks, the AMS detector will sit in the shuttle's cargo bay, which can be opened up as a particularly posh convertible. The plan is to fly part-time with the shuttle "upside down", its opening facing the Earth, to measure directly the "albedo" of cosmic rays bouncing up after hitting the top layers of the atmosphere. If all goes well, the AMS would be added, in the year 2000, to the International Space Station *Alpha* for continued operation, lasting several years. My hunch is that AMS was not approved because of its capability to search for cosmic-ray antinuclei. That is far too long a shot to move a committee. It must have been approved because of the observational improvements it will bring in "orthodox" areas of physics such as the measurement of the low-energy $\bar{p}$ flux, an indirect window into the annihilation of halo super-wimps[32], as we have already mentioned.

Even more conservatively, AMS will constitute an enormous step in our knowledge of the spectra of conventional (matter) cosmic-ray nuclei. Various flux ratios, such as ^{9}Be/^{10}Be, B/C, ^{3}He/^{4}He will be measured with unprecedented precision, and we have discussed how crucial they are to our understanding of cosmic rays. Most importantly, AMS will be the first detector sensitive to extragalactic cosmic rays, and this is where the serendipitous surprises may lie.

Acknowledgments

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